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14. ABSTRACT

This project established the national center of excellence in microplasma science and technology at Saint Peter's College in Jersey City, New Jersey. The Center for Microplasma Science and Technology (CMST) seeks to serve as the scientific and educational forum devoted entirely to this emerging field in the United States. The CMST at Saint Peter's College was envisioned to allow a national base of operations to help mediate and comprehensively organize all national research efforts in this field for defense and other key national interests. CMST seeks to function as a meeting point for scientific meetings, workshops, and conferences, and as a clearinghouse to establish cross-fertilization efforts between microplasma research and other related scientific fields. Locating the center within a higher education context is envisioned to stimulate educational outreach to young scientists and underrepresented minorities pursuing scientific careers.

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FINAL REPORT

Air Force Office of Scientific Research

Grant # FA9550-09-1-0284

"(CONGRESSIONAL) CENTER FOR MICROPLASMA SCIENCE AND TECHNOLOGY"

Period: July 1, 2009 - December 31, 2011

Prepared by
Professor Jose L. Lopez, PhD[1]
Professor WeiDong Zhu, PhD[2]
Department of Applied Science & Technology
Saint Peter's College
2641 John F. Kennedy Boulevard
Jersey City, New Jersey 07306

1. Email : jose.lopez1@shu.edu (current affiliation w/ Seton Hall University, Department of Physics, South Orange, New Jersey 07079); Telephone: (973) 761-9057
2. Email: wzhu@spc.edu; Telephone: (201) 761-7923

I. SUMMARY OF ACCOMPLISHMENTS

With the support of AFOSR Grant # FA9550-09-1-0284, Saint Peter's College (SPC) established a Center of Excellence in microplasmas known as the *Center for Microplasma Science and Technology* (CMST). The establishment of a National Center of Excellence in microplasma science and technology was the first and only topical scientific and educational forum devoted entirely to this emerging field in the United States. The requested funding was meant to create a hub for what a fragmented effort of university and industrial research and development laboratories located all across the country attempting to focus on microplasmas. The establishment of CMST seeked to form a national base of operations to help mediate and comprehensively organize national research efforts in this field for defense and other key national interests. The Center was intended to function as a microplasma community organizer serving as a meeting point for scientific meetings, workshops, and conferences, and as a clearinghouse to establish cross-fertilization efforts between microplasma research and other related scientific fields. CMST was established to function as an independent basic and applied scientific research facility in microplasmas seeking to provide both educational and commercialization capabilities for the benefit of the Nation. The idea to locating the Center within a higher education context was to stimulate educational outreach to young scientists and underrepresented minorities pursuing science careers. Saint Peter's College was seen as an ideal location for the CMST since it is situated in one of the most culturally diverse areas in the world. This cultural diversity of students, faculty, and staff mixed with the strong liberal arts curriculum provided by the College was expected to enhance the overall quality of the educational experience. A further strength of SPC as the site for the CMST was its central location within the New York-New Jersey metropolitan area where various high technology companies are located as well as a region where approximately 40% of the national gross domestic product is generated in United States. In addition, numerous important Department of Defense facilities such as Picatinny, Fort Monmouth, Fort Dix, Naval Air Engineering Station Lakehurst, and McGuire Air Force Base are located in close proximity, as well as the Princeton Plasma Physics Laboratory, a Department of Energy national laboratory dedicated to the use of equilibrium or hot plasmas for fusion energy research.

The CMST further benefited from the well-respected and established work of Professors Jose L. Lopez and WeiDong Zhu, two internationally recognized experts in the field of microplasmas. Lopez and Zhu were the founders of the *Center for Microplasma Science and Technology* at Saint Peter's College with Professor Lopez serving as Director and Professor Zhu as Director of Research. A full-time staff of a Director of Educational Outreach, a Director of Technology, two post-doctoral research scientists, and one graduate student / lab technician were hired as the staff of CMST. During the two year duration of the project, a total of eighteen undergraduate, ten high school students, and one graduate student were directly supported by this project. CMST further hosted eight additional local area high school students and four teachers as summer and after-school guest researchers funded through external collaborative projects. CMST hosted in 2009 and 2010, the Hudson County Science Fair for local area high school students. In the summer of 2011, CMST hosted the first-ever United States Microplasma Community

Meeting in Jersey City, NJ which gathered of all the major US microplasma researchers. This two year grant further enhanced existing work being done collaboratively by Professors Lopez and Zhu through a previous and temporally overlapping AFOSR Grant # FA9550-08-1-0332. The final report for this previously funded AFOSR funded grant project intimately connects with the described research work in this current final report. A further six month no cost extension from July 1st to December 31st, 2011 was requested and accepted to allow the completion of Master's Thesis research work by Mr. David Jacome, a graduate student at Stevens Institute of Technology (Hoboken, NJ) and the Fall semester sabbatical stipend and sabbatical stay of Professor Kevin Martus from William Paterson University of Wayne, NJ.

During June 2011, the President and Provost of Saint Peter's College decided to laid-off the entire grant supported full-time staff of CMST. Professor Lopez, the Principle Investigator left his physics professorship at SPC for a new professorship position at Seton Hall University. Professor Zhu remained as the only staff member of CMST and has assumed the directorship role. There is an anticipated new physics faculty hire for Fall 2012 that is expect to be part of the CMST staff. There has not been any further internal college funding resources provided to CMST. The future continuity of CMST is not known at the current time of the writing of this final report, but the organizational, research, and outreach objectives for this AFOSR funded project have been met.

II. DESCRIPTION OF MAJOR ACCOMPLISHMENTS

2.1 The Homogeneous Dielectric Barrier Discharge (DBD)

Dielectric barrier discharges (DBDs) are normally filamentary in character. This has limitations when used in surface modification applications for uniform treatment of materials. By applying a high voltage shorting pulse on the order of 10 ns, however, the result is a diffuse, uniform discharge.

The original discharge chamber is a rectangular Pyrex tube 1 cm by 2.5 cm with a magnesium fluoride (MgF_2) window attached to the front for UV detection. Two rectangular copper electrodes straddle the discharge tube behind the MgF_2 window. The bottom electrode is grounded, and the top electrode is connected to the power supply. A fast high-voltage solid state switch is used to apply shorting pulses with a fall time of approximately 10 ns to the top electrode. This sharp falling edge releases the charges deposited on the dielectric surface; the plasma forms only during this rapid drop of the applied voltage. The pulse repetition could be varied from zero to 30 kHz.

For vacuum ultraviolet (VUV) optical emission spectroscopy, as well as imaging of the plasma footprint, several important modifications to the discharge chamber and apparatus were necessary (Figure 1).
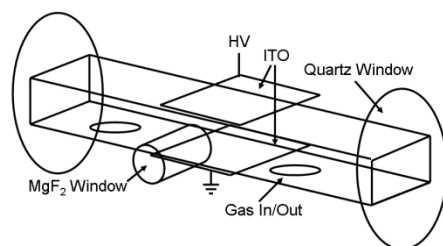
Figure 1. Schematic of the updated discharge tube.

A new quartz discharge tube was constructed with an extended "nose" to which the magnesium fluoride window (MgF_2) is attached for coupling to the entrance window of the VUV spectrometer. For imaging of the plasma footprint, indium tin oxide (ITO) transparent electrodes 2.2 cm by 2.5 cm replaced the original copper electrodes. Finally, digital mass flow controllers and pressure gauges were added for more accurate pressure and flow monitoring.

High pressure DBDs are well-known sources of excimer emissions from rare gases. These high energy emissions are capable of breaking most chemical bonds, so they initiate chemical reactions or modify surface properties. The vacuum ultraviolet (VUV) emissions in pure Ar were measured as a function of pressure (300 – 600 Torr) and gas flow rate.
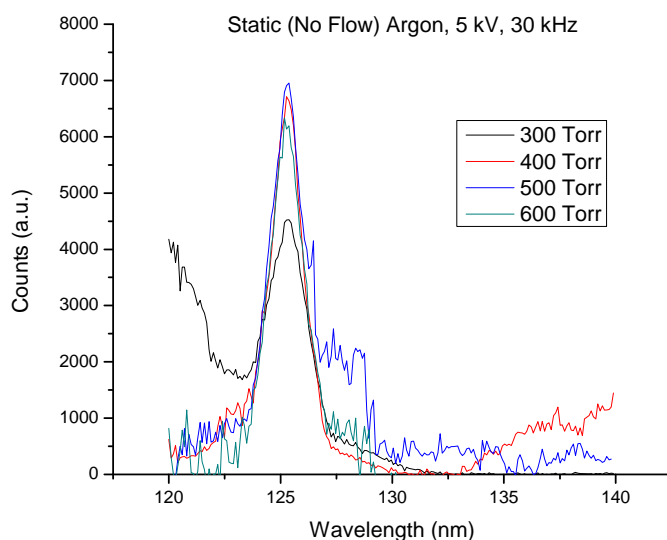
Figure 2. Argon excimer emission as a function of pressure

The Ar_2^* excimer emission (126 nm) appears most prominently at a pressure of around 500 torr (Figure 2). As the pressure increases from 300 to 500 torr, the intensity increases because the rate of three-body collisions, which are necessary for the formation of the Ar_2^* excimer, begins to dominate over the rate of two-body collisions that quench excimer formation. As the pressure increases beyond 500 torr, the gas density becomes

high enough so that quenching of both excited Ar (precursors for excimer formation) as well as excimer molecules prevents a further increase of excimer emission (Equations (1) and (2)).

$$Ar + e \rightarrow Ar^* + e \qquad (1)$$
$$Ar^* + Ar + Ar \rightarrow Ar_2^* + Ar + e \qquad (2)$$

Interestingly, static Ar gas (no flow) resulted in higher emission of the Ar_2^* excimer in comparison to the flowing Ar at 0.7 slpm, which instead displayed a large peak at 130 nm due to atomic oxygen (OI, $^3P - {}^3S_0$) (Figure 3).
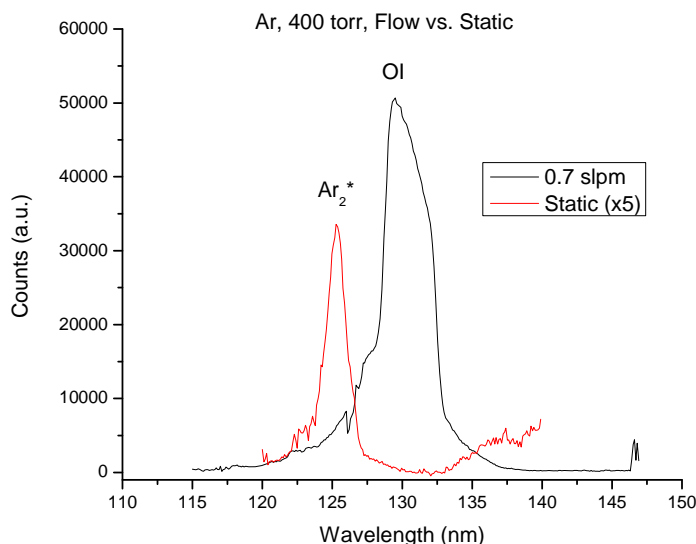
Figure 3. Flow dependency of VUV emission

The presence of oxygen is simply due to impurities in the gas mixture. This OI emission line is likely due to collisional energy transfer from Ar* metastables to O atoms. VUV emission from pulsed DC excitation was compared to emission from an AC high voltage power supply (5 kV, 30 kHz).
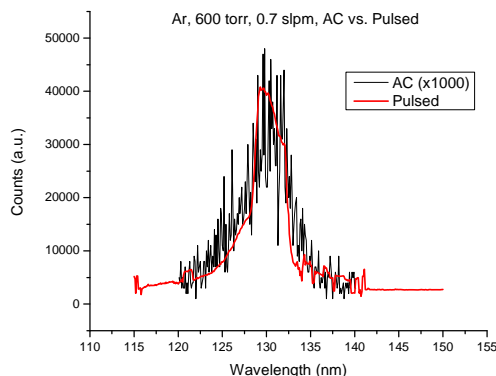

Figure 4. VUV emission from AC excitation vs. pulsed HV excitation

Emission from the Ar$_2$* excimer is not present, but the OI line at 130 nm is still apparent. Moreover, the DBD assumes its more typical filamentary state as opposed to the homogeneous mode obtained by using fast high voltage pulses. The purpose of generating high, short-lived electric fields is to enhance the generation of specific radicals, excited species, and UV/VUV radiation, which can clearly be observed in this work.

Finally, the new transparent electrodes allows for imaging of the plasma footprint on the dielectric surface. From low pressures up to around 150 torr, essentially the entire volume between the electrodes is filled with a uniform purple glow. Continuing to increase the pressure results in a progressively more localized plasma. At precise operating conditions (380 torr, 1.0 slpm), the plasma changes from a normally bright, diffuse discharge into multiple rapidly moving filaments (

Figure 5). The footprints of the filaments form well-known Lichtenberg figures, which are patterns on a dielectric resulting from a high electrical potential and whose shape is dependent on the polarity and time variation of the applied potential. The observed plasma filaments are cathode-directed streamers with positive charges accumulating on the ground electrode.
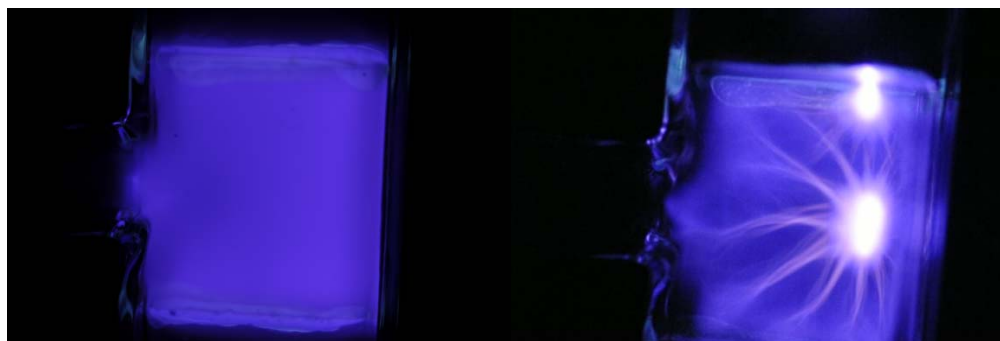

Figure 5. Left, "normal" homogeneous glow mode viewed through the top electrode; Right, filamentary mode.

A major improvement to the circuitry of the high voltage switch is in progress. Currently, the switch itself (Behlke HTS 150) is housed in a Faraday cage to eliminate electromagnetic noise. However, several other circuit elements, including charging capacitors, a resistor, wire leads, and the DBD itself are all external. The electrical interference from these elements at the VUV spectrometer is significant; while the high voltage is pulsing, the background counts are at least 10,000, and the spectral signal (only a few thousand counts more) is buried. This prevents us from obtaining high resolution VUV emission spectra. To fix this, only non-inductive capacitors and resistors will be used, and a new Faraday cage will be built to contain everything. A coaxial cable will carry the high voltage pulse to the DBD, which will also be housed in a grounded box during spectral readings. Following this improvement, high resolution UV/Vis spectra will be taken, and the rotational temperature will be obtained from NO and OH emissions by comparing to simulation. Additionally, the total UV/VUV radiation will be determined for specific wavelengths.

2.2 The Capillary Dielectric Barrier Discharge (Cap-DBD)

The Capillary Dielectric Barrier Discharge (Cap-DBD) reactor consists of metal wire electrodes inside quartz capillary tubes powered with a low kilohertz frequency AC high voltage power supply. An advantage of these Cap-DBDs over planar or coaxial DBDs is their geometry; the open space surrounding each tube allows active species created by the plasma to move freely about the structure. In addition, they can be assembled in various configurations, e.g. planar, multi-layer, and cylindrical (

Figure 6).

Figure 6. Cap-DBD in air: 12" planar, 1x10, 250 μm gap width (left); 6" 3-D, 3x6, 250 μm gap width (middle), 12" cylindrical, 20 tubes, 0 μm gap width (right).

Cap-DBDs are ideal for applications such as the inactivation of microorganisms in air. The electrical and emission properties of the Cap-DBD plasma in both atmospheric pressure air and Ar (200 – 850 Torr) were investigated. For the electrical and spectral measurements in air, three reactors, each with six tubes, six inches in length, were assembled with gap widths of 500 μm, 225 μm, and 0 μm (i.e. tubes touching). Typical waveforms for applied voltage and discharge current are shown in **Figure 7**. As in most atmospheric pressure DBDs, the current flow and power dissipation occurs in a large number of short-lived microdischarges.
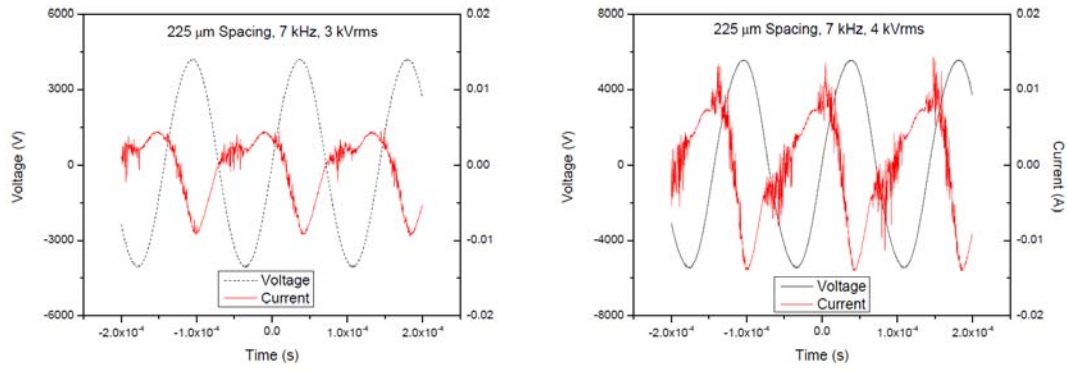
Figure 7. Current-voltage waveforms for a six-tube, six inch, 225 5 μm gap reactor at different applied rms voltages.

When the sinusoidal voltage is applied to the reactor, there are periods of discharge activity when the voltage is high enough for breakdown to occur, as well as periods of inactivity when the applied voltage is below the necessary level. To obtain the consumed power, we use voltage/charge Lissajous figures. The transported electrical charge Q through the reactor is plotted as a function of the applied voltage through one period. This charge is derived from the voltage drop U across a measuring serial capacitor C; in the present study, $C = 47$ nF. The area of the closed loop of one period of the applied voltage vs. the charge, the area of the Lissajous figure, is equal to the energy dissipated in one cycle. The average discharge power is then simply the energy dissipated times the applied frequency, $P = Wf$.

Figure 8 (left) shows the influence of applied voltage on the Lissajous figures. Increasing the voltage not only increases the overall area, but it also increases the slope of the discharge part of the curve (sides AB and CD), which corresponds to the capacitance of the dielectric(s) and the plasma. The sides BC and DA, where there is only displacement current, correspond to the capacitance of the electrode configuration in the absence of plasma. The gap width between tubes influences both the area and shape of the Lissajous figures (
Figure 8, middle). For the larger spacing, the decreased slope dQ/dV of sides BC and DA indicates a decreased reactor capacitance when compared to the smaller spacing. The average discharge power is plotted as a function of voltage in
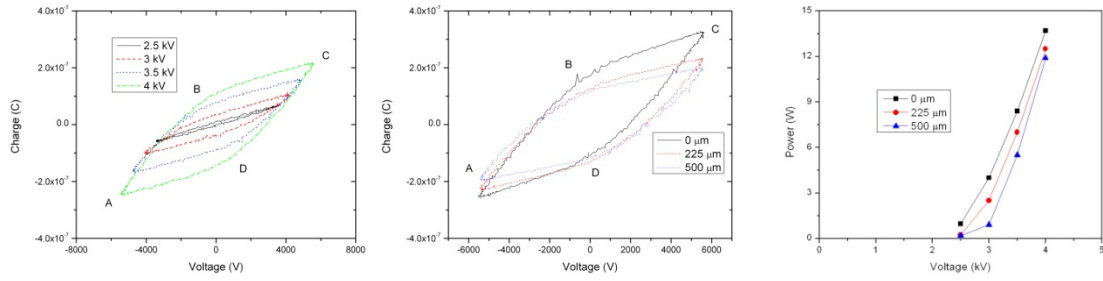**Figure 8**, right.

Figure 8. Left: Influence of applied voltage on Lissajous figures for a six-tube, six inch, 225 μm gap reactor; Middle: Dependence on gap spacing for 0 μm, 225 μm, and 500 μm with an applied voltage of 4 kV; Right: Average discharge power for three reactors (0 μm, 225 μm, and 500 μm) as a function of applied voltage.

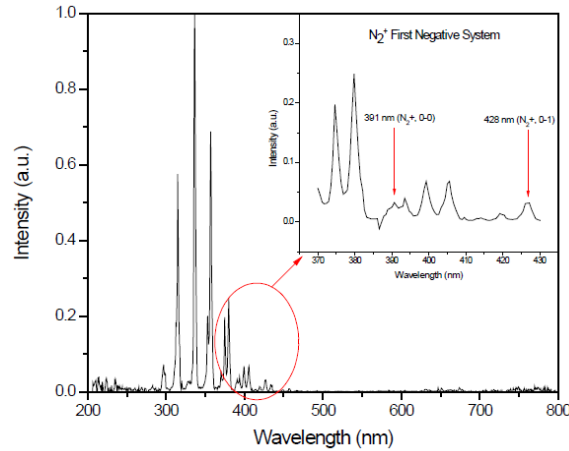Figure 9 shows a typical spectrum of the emission from the Cap-DBD air plasma at 7 kHz, 4 kV rms.

Figure 9. Optical emission spectrum of the atmospheric air plasma for a 225 **μ**m reactor.

The prevalent peaks are in the second positive system of N_2 ($C^3\Pi_u - B^3\Pi_g$), as well as two peaks in the first negative system of N_2^+ ($B^2\Sigma_u^+ - X^2\Sigma_g^+$) at 391 nm and 428 nm. Emission of light at 391 nm requires 18.7 eV electron energy; the low relative intensity of this peak is indicative of a small number of energetic electrons. In addition, rapid quenching of atomic oxygen by N_2 and O_2 results in a lack of emission at 777 nm and 845 nm ($^5S_o - {}^5P$ and $^3S_o - {}^3P$, respectively).

As a supplement to our spectroscopic data, we also took some preliminary ozone measurements for each of the three (0 μm, 225 μm, and 500 μm) reactors running at 3 kV. The reactor was contained in a chamber and ozone was sampled at the exit directly into the ozone analyzer at a rate of approximately 1 L/min. The respective ozone

concentrations were about 660 ppm, 550 ppm, and 380 ppm, corresponding to the decrease in power with increasing gap width. Increasing the input voltage beyond 3 kV resulted in ozone concentrations which were beyond the range (0.01 – 900 ppm) of our ozone analyzer. For a device of such small scale, these ozone levels are promising and will be the subject of future investigation.

A 4 tube, 0 μm gap width, 6 inch planar reactor was assembled for Ar spectral measurements. The reactor was contained in a stainless steel chamber which was evacuated with a roughing pump to a base pressure of about 5 mTorr. The vacuum pressure and gas pressure were measured with respective thermocouple gauges, and the flow rate was maintained at 100 – 200 mL/min to keep the Ar gas fresh. The applied voltage was 1.5 – 2 kV (RMS) at a frequency of about 29 kHz.

The UV/Vis emission spectrum of Ar (Figure 10) is dominated at lower pressures (200 – 500 Torr) by impurities with a strong second positive system of N_2 ($C^3\Pi_u - B^3\Pi_g$). As the pressure increases, Ar spectral lines from 700 – 850 nm increase. At atmospheric pressure (top right), other active species are apparent, including NO (A-X) from 225 – 275 nm and a very strong OH (A-X) line at 309 nm. At 850 Torr, most of the impurities have disappeared and the spectrum is predominantly Ar.
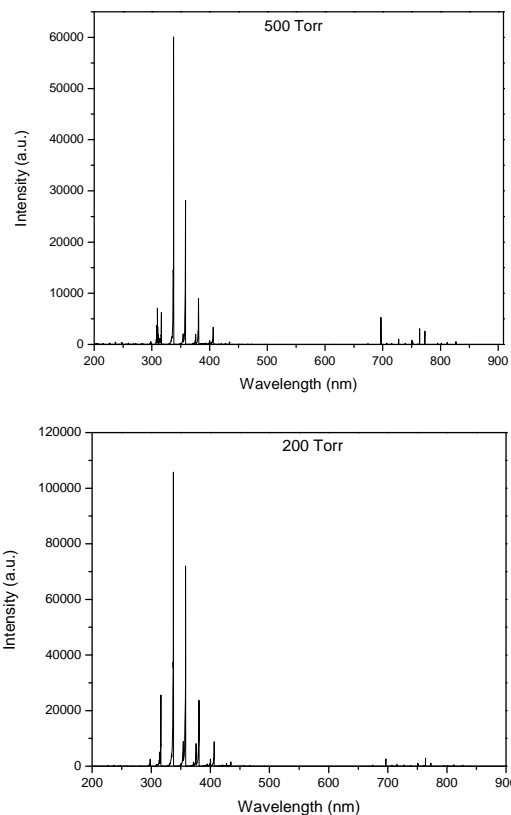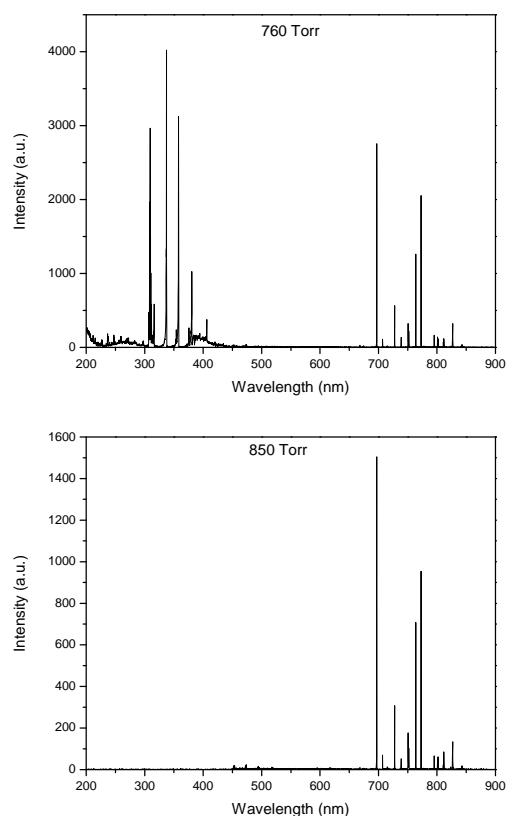
Figure 10. Optical emission spectrum of the Cap-DBD in Ar at different pressures: 200 Torr (top left), 500 Torr (top right), 760 Torr (bottom left), and 850 Torr (bottom right).

Figure 11). The measured (blue) and calculated (violet) spectra are compared using LIFBASE, a spectral simulation program of diatomic molecules. The average gas temperature at 760 Torr is approximately 345 K, with a peak correlation of 0.98.

Future work on the Cap-DBD includes more extensive ozone measurements for possible applications as a portable ozone generator. An ozone analyzer with a larger capacity (> 900 ppm) will be necessary. Further studies of excimer emission will include VUV measurements in Ar, as well as optical emission studies in rare gas-halogen mixtures, such as ArF and KrI.
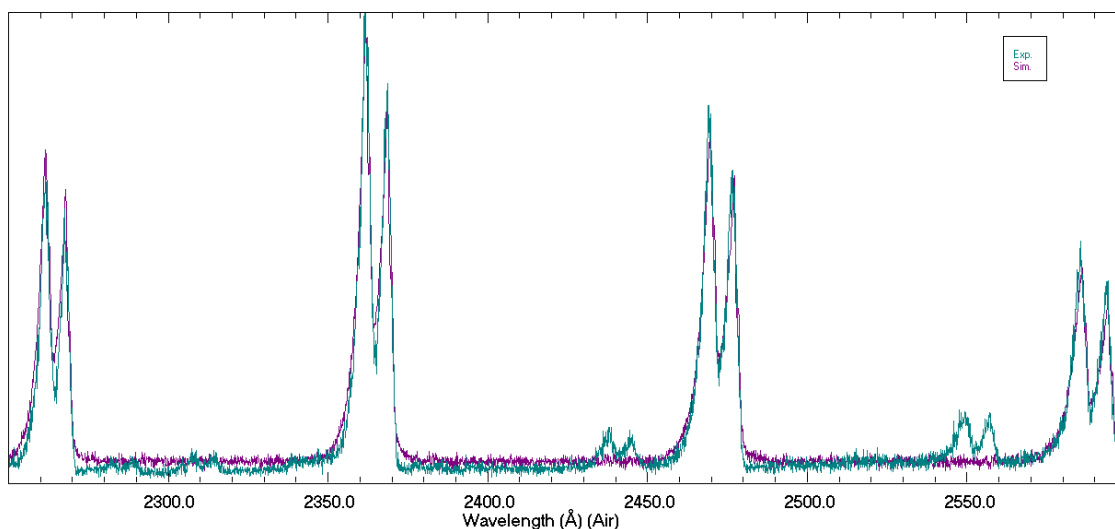
Figure 11. Measured (blue) vs calculated (violet) NO (A-X) spectra using LIFBASE

2.3 Flexible Tubing Plasma Jet (a.k.a plasma snake)

We made the device using Ar and He as working gases, Teflon tubing, copper tape as electrode(s) and a homemade power supply. We have made straight plasma snakes with only 1 plasma plume coming from the end of the tubing and snakes with multiple shorter plasma plumes from alumina tubing protruding from points along the length of the Teflon tubing (we call these plasma brushes). The configuration of the plasma brushes can be tailored to the application.

We are suggesting the novel applications of plasma cleaning of the inner surface of medical tubing and a plasma brush cleaner device for complex geometries based on our results.
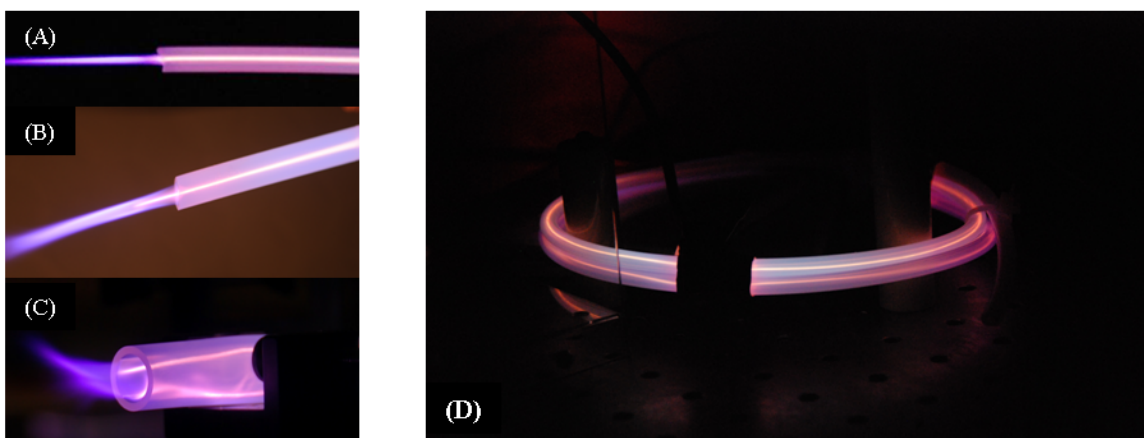

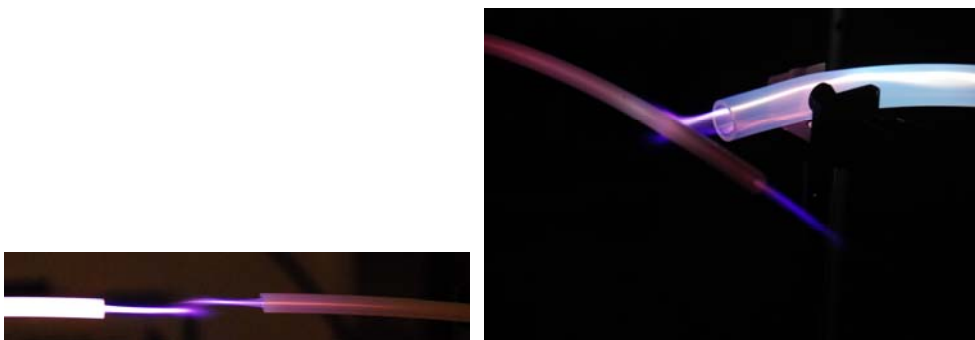**Figure 12.** Images of our samples in operation.

Figure 13. The images show the previously observed ability of the plasma plume of a powered sample to induce a plasma within the tubing of an unpowered sample with He gas flowing.

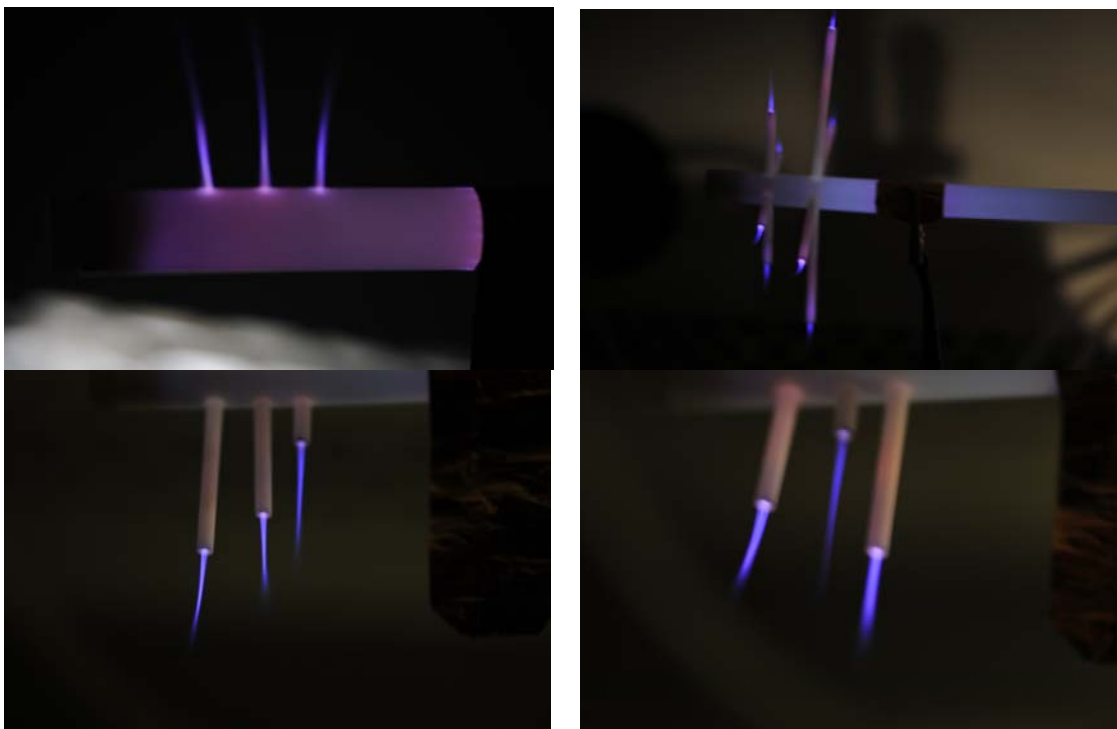**Figure 14.** A close-up of the plasma plume being divided when scissors are held close as a local ground.

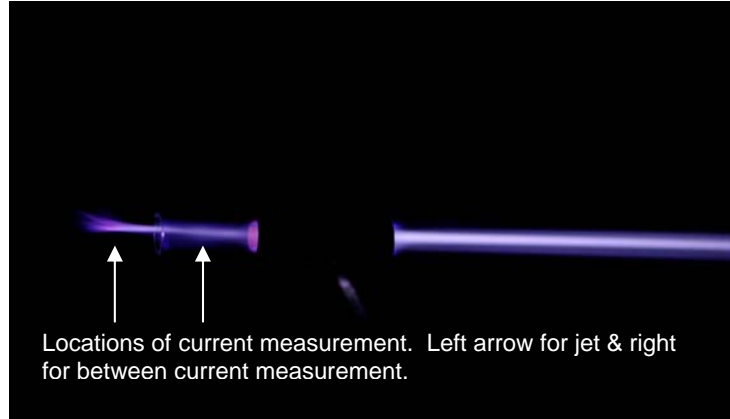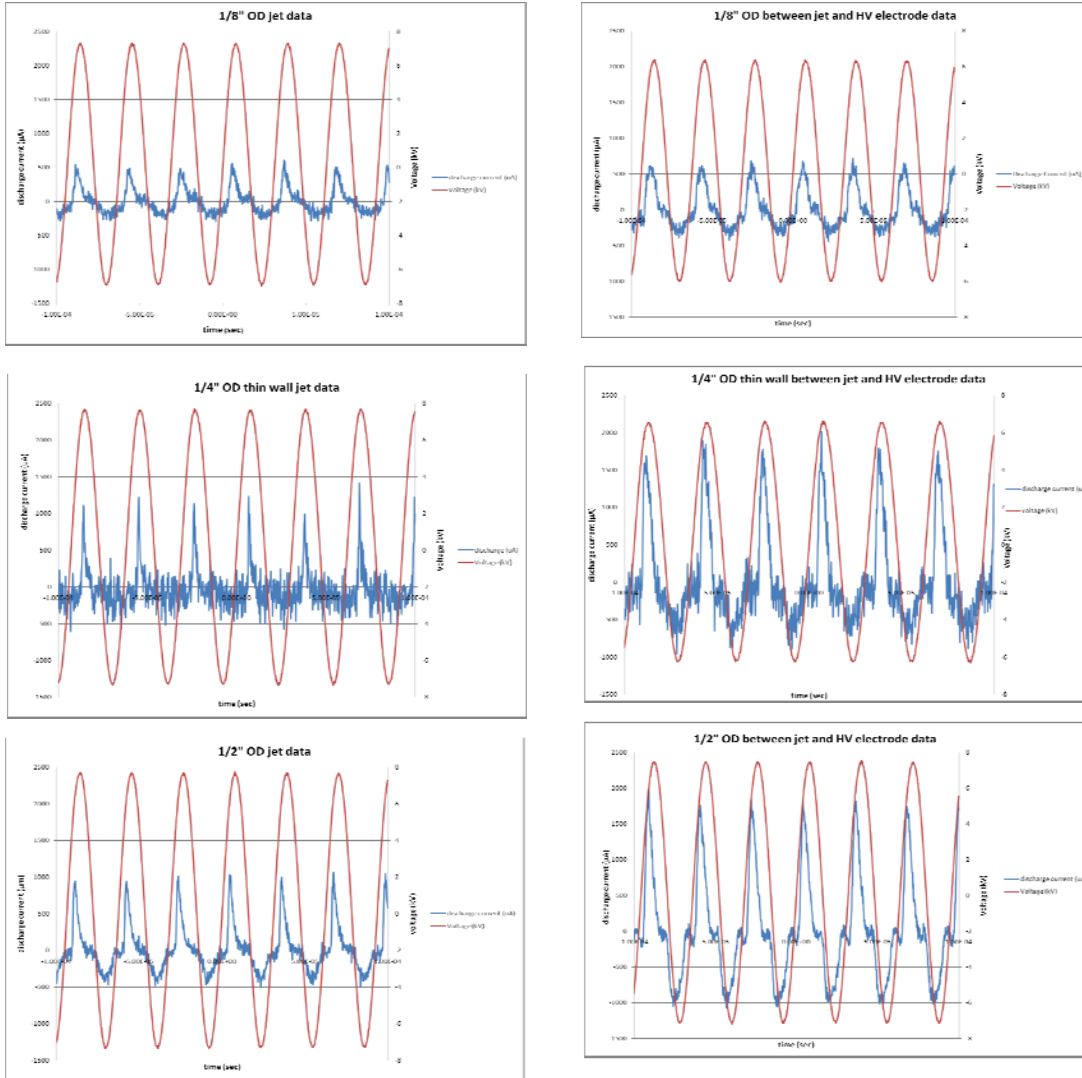**Figure 15.** Close-up image of the plasma brush.

Figure 16. The difference in these current curves may provide some insight into the physics of the plasma snake.

	1/8" OD 1/16" ID	1/4" OD 3/16" ID	1/2" OD 3/8" ID
Jet power (W)	V_{RMS}=5.3 kV, I_{RMS}=215 μA 1.13	V_{RMS}=5.6 kV, I_{RMS}=316 μA 1.77	V_{RMS}=5.2 kV, I_{RMS}=346 μA 1.81
Filament power between jet and HV electrode (W)	V_{RMS}=4.6 kV, I_{RMS}=317 μA 1.44	V_{RMS}=4.6 kV, I_{RMS}=710 μA 3.27	V_{RMS}=5.2 kV, I_{RMS}=768 μA 3.96

Table 1. Calculated powers for samples and at different positions.

Optical Emission Spectroscopy (OES) was performed for pure He and He+O_2 mixtures show how dependent the presence of active species is on gas composition and flow rate.

A large amount of N_2^+ (391.4 nm) is formed in pure He with a measureable amount of excited atomic O (777 and 844 nm peaks) and excited He (706 nm peak is associated with energetic electrons of He). Penning ionization occurs when He metastables meet air causing high N_2^+ concentrations.[1,2]

For different concentrations of O_2 gas added to the He (0.5, 0.75, 1, 1.25, 2%), flow rate of 5 slm, higher amounts of excited atomic O and excited He at the expense of N_2^+. The smallest amount of oxygen (0.5% O_2) brings the greatest increases in He and O and N_2 levels and greatest decreases in N_2^+.

Different flow rates for He + 2% O_2 gas composition was a test for how to increase different species concentration. Lowering the flow rate from 5 slm to 2 slm increased the N_2^+ levels and decreased the N_2 levels, increasing from 5 slm to 8 slm decreased all concentrations.

Pure He was compared to pure Ar. Pure He is more effective at generating N_2^+ and atomic O than Ar. Since He also requires less voltage for breakdown it is the more attractive gas.

Jet gas temperatures along the length of the plume can be estimated using OES data and LIFBASE. With more O_2 added as the jet temperature increased slightly as Pure He - 310 K, He + 0.5% O_2 and He + 1% O_2 - 315 K, He + 2% O_2 – 320K.

Future Work

One, a more appropriate power supply could be obtained. Either a power supply that matches the impedance with the impedance of the device or an accompanying impedance matching circuit is needed. We have had access to neither thus far.

Two, a different electrode material should be used, instead of simply copper tape with conductive adhesive wrapped around the tubing. A material that does not get too hot during use is needed because the Teflon has a low melting temperature and starts to droop after about 5 minutes of operation. Also, since the goal of the project is to try to

determine whether the plasma could remove all harmful and/or active residues from tubing used for medical applications, its effects should be easily separated from those due to heating of the tubing. Also, since the plasma is being used as an alternative to heat to avoid degradation of the tubing, excess heating must be avoided.

Three a fundamental study of the plasma physics is needed to ascertain the origin of the axial filament seen in the single plume samples. In the plasma brushes, the division of current should also be studied. The difference is shape of the current curves in the I-V data could be explained by this work.

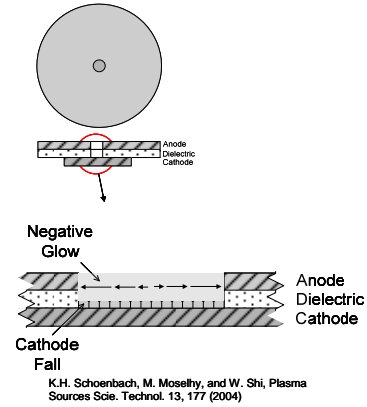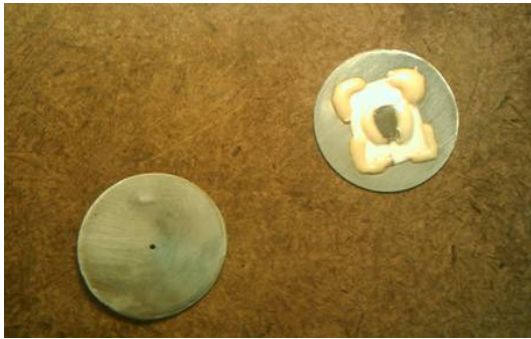## 2.4 Cathode Boundary Layer Discharges (CBLDs)

Figure 17. CBLD picture and schematic. .

We concentrated on the intrinsic properties of the cathode materials to develop a basic understanding of the origin of self organization patterns. Eight different cathode materials (Al, Cu, Ti, W, Mo, Hf, Ni and Ag) and 2 different dielectric materials (silica and alumina) were used. Molybdenum was the only anode material used.

	magnetic ordering	magnetic susceptibility ($*10^{-6}$ cm^3/mol)	conductivity (MS)	Work function (eV) lowest value reported	Secondary electron emission ratio (average # of secondary electrons emitted for every primary electron)	Self-organization? @ 100 Torr
Cu	diamagnetic	-5.46	58.411	4.48	1.3	No
Ag	diamagnetic	-19.5	61.843	4.52	1.5	Yes
Ti	paramagnetic	+151	2.564	4.33	0.9	Yes
Hf	paramagnetic	+71	2.967	3.9	Not available	Yes
Mo	paramagnetic	+72	18.282	4.36	1.25	Yes
W	paramagnetic	+53	18.553	4.32	1.4	Yes
Al	paramagnetic	+16.5	36.914	4.06	1.0	No
Ni	ferromagnetic	n/a	14.045	5.35	1.3	No

Table 2. A summary of the electrical and magnetic properties for cathode materials used in self organization study.

Self Organization Data

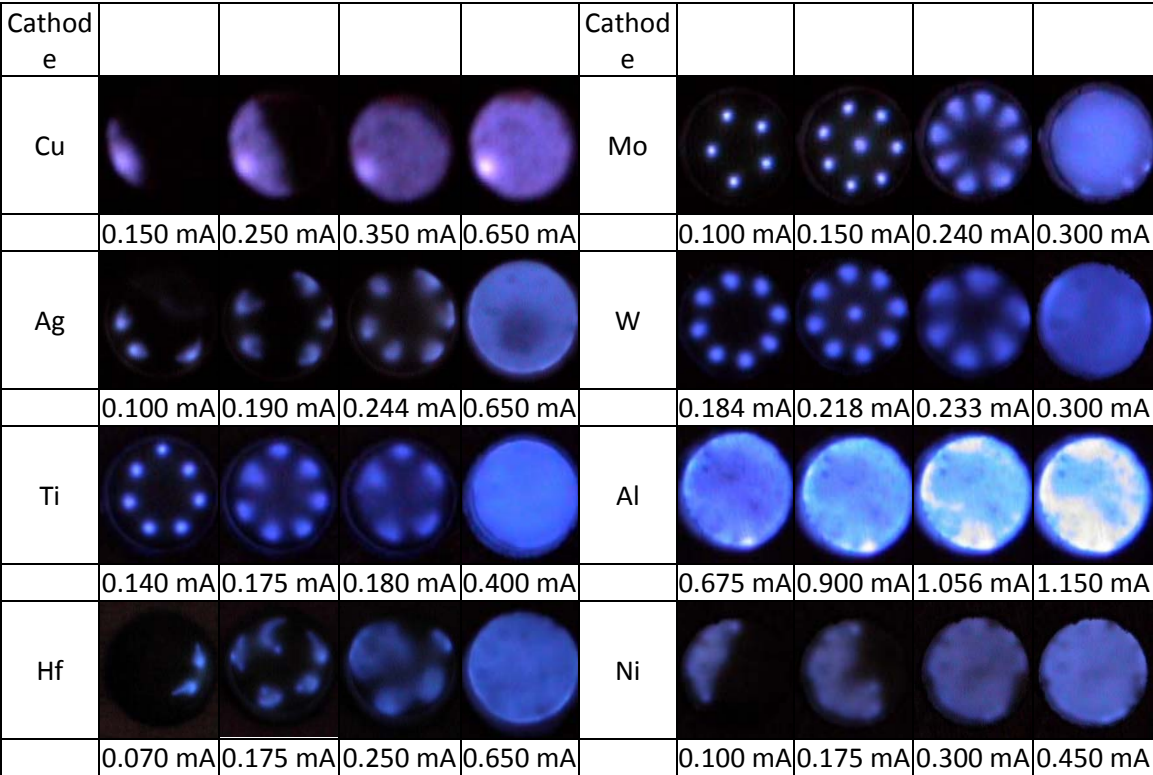There is also data for 250 Torr and 75 Torr for silica as dielectric.

Cathode					Cathode				
Cu					Mo				
	0.150 mA	0.250 mA	0.350 mA	0.650 mA		0.100 mA	0.150 mA	0.240 mA	0.300 mA
Ag					W				
	0.100 mA	0.190 mA	0.244 mA	0.650 mA		0.184 mA	0.218 mA	0.233 mA	0.300 mA
Ti					Al				
	0.140 mA	0.175 mA	0.180 mA	0.400 mA		0.675 mA	0.900 mA	1.056 mA	1.150 mA
Hf					Ni				
	0.070 mA	0.175 mA	0.250 mA	0.650 mA		0.100 mA	0.175 mA	0.300 mA	0.450 mA

Figure 18. Alumina as Dielectric at 100 Torr

Cathode					Cathode				
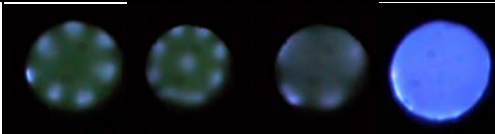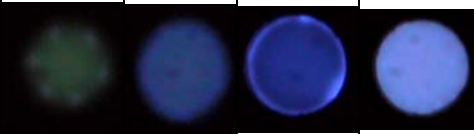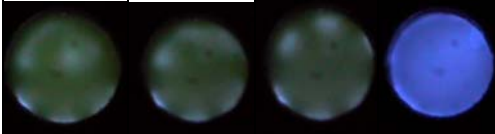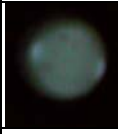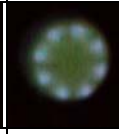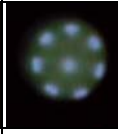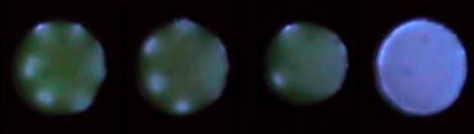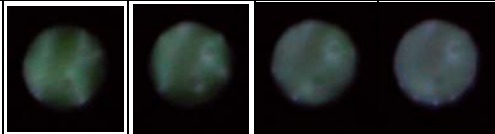
Figure 19. Silica as Dielectric at 100 Torr.

Comparison of the two data sets seems to indicate the dielectric does affect the plasma behavior as expected. First, the minimum current levels and current range of self organization are higher for the silica samples than for the alumina samples. Also, the silica with its dielectric constant of ~3 would theoretically hold less charge than alumina with its dielectric constant ~9.8. Less charge accumulated at the dielectric surface means less charge is present to facilitate plasma formation and less charge and/or plasma to respond to magnetic behavior of the cathode material. The silica samples have less clearly defined elements that the alumina samples and some homogenous plasma seems to be present even when self organization is seen. The exception is the Hf cathode sample which has more clearly defined elements with silica as the dielectric. In addition, the self organized plasma seems to be closer to the dielectric wall for the silica samples than the alumina samples

Xe Excimer Emission Data

CBLD devices are also known to support excimer emission for these cathode materials when operated in Xe, Xe_2^* wavelength is 172 nm. It may be that there is a correlation between excimer emission and self organization patterns especially since the maximum excimer emission is at lower current levels, approximately at the levels where self organization patterns are formed.
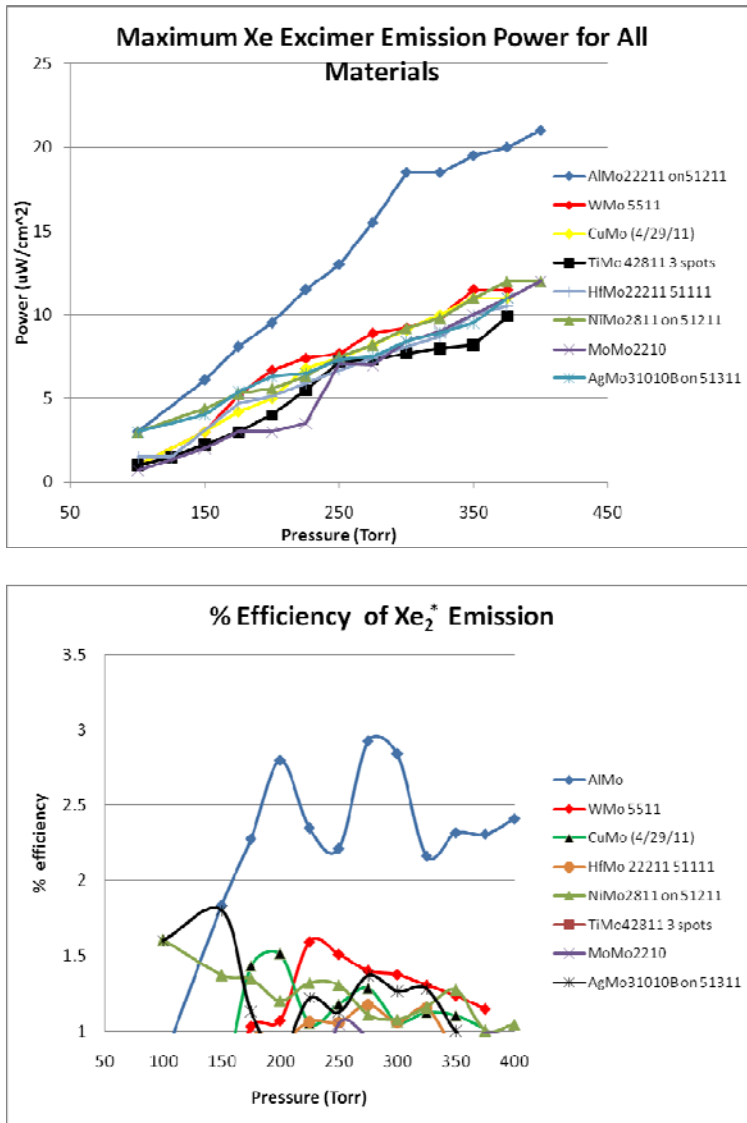
Figure 20. Eximer emission power and efficiency data..

Material	Reflectivity at 172 nm	Fraction of kinetic energy transferred between metal and Xe	Secondary electron emission ratio
Al	0.9265	.28	1

W	0.593	.49	1.4
Ni	0.282	.43	1.3
Cu	0.2505	.44	1.3
Ti	0.175	.39	.9
Mo	0.548	.49	1.25
Hf	0.204	.49	?
Ag	0.1765	.5	1.5

Table 3. Materials properties that are possibly relevant to excimer emission study.

Based on these data and the values in Table 3, the characteristic of the cathode material most influencing excimer emission is the fraction of kinetic energy transferred between metal and Xe. Aluminum is the clear standout for excimer emission efficiency and power in this series of materials and had the lowest amount of kinetic energy lost to the material. The similarity in fraction of kinetic energy transfer values for the other materials is corresponds to the similarity inperformance. The same is true for the secondary electron emission ratio values. The variability in the reflectivity at 172 nm seems to indicate it is not an important parameter.

Future Work

For further excimer emission studies, more metals that have low atomic masses should be used as cathode materials. In addition, alumina as a dielectric should be tested to see if excimer emission behavior has the same dependence as self organization. Finally, higher pressures could be tested. So far we have stayed below 400 Torr because we do not study self organization above 250 Torr and were interested in the correlation between the two phenomena.

More work on self organization is needed to confirm our theories. Certainly more materials should be tested, especially more diamagnetic materials with large electrical conductivities such as gold and indium; and stronger paramagnetic materials with lower electrical conductivities such as zirconium (especially to replace the confusing Hf) and lutetium. The amount of charge accumulated on the dielectric surfaces should also be measured; or we could use another dielectric material as spacer. Other measurements would be the current and magnetic field at different points along the cathode surface before and while the patterns are (or are not) forming. It is difficult to actually carry out these last two measurements in the current setup. However, perhaps using a larger version of the device and a different orientation would allow us to experimentally obtain the measurements.

Modeling would also be helpful. Some representations of current gradients and magnetic fields as functions of time and current level could lend strong support to these theories. In addition the plasma arrangement at different time points could make the effect of the

magnetic field on when and how self organization patterns form more obvious or point in other directions for possible explanations.

III. PUBLICATIONS

Select Conference Presentations and Posters:

5th International Workshop on Microplasmas: Fundamentals and Applications, March 1-5, 2009, San Diego, CA, USA
1. W. Zhu, J. Lopez and K. Becker, Atmospheric Pressure Plasma Micro Jet - Its Interaction with Bacteria in Air and in Liquid Media (Invited Talk)
2. W. Zhu, L. To, J. Lopez and K. Becker, Direct Current Cathode Boundary Layer Xenon Discharges (Poster)
3. J. Lopez, D. Jacome, W. Zhu, M. Figus and K. Becker, Study of the Operational Properties of the Capillary Plasma Electrode (CPE) Discharge (Poster)
4. J. Lopez, W. Zhu and K. Becker, Time-Resolved Investigations of a Fast-Pulsed Dielectric Barrier Discharge (Poster)

2nd International Conference on Plasma Medicine, March 16-20, 2009, San Antonio, Taxas, USA
1. W. Zhu, J. Lopez and K. Becker, Interaction of an Atmospheric-Pressure DC Plasma Micro Jet (PMJ) with Bacteria and Liquid Media (Talk)

37th IEEE International Conference on Plasma Science, June 20-24, 2010, Norfolk, VA, USA
1. W. Zhu, J. Lopez and K. Becker, Optical emission study of a direct-current, atmospheric-pressure non-thermal Plasma Micro Jet (Talk)
2. J. Mahoney, W. Zhu, J. Lopez, V. Johnson, Electrical and Optical Emission Measurements of a Capillary Dielectric Barrier Discharge (Poster)
3. V. Johnson, W. Zhu, L. To, J. Lopez, Self Organization Trends in Cathode Boundary Layer Discharge (CBLD) Devices for Various Cathode Materials (Poster)

63rd Gaseous Electronic Conference, October 4-8, 2010, Paris, France
1. W. Zhu, J. Lopez and K. Becker, Optical Emission Study of a direct-current, atmospheric-pressure non-thermal Plasma micro jet (Poster)

6th International Workshop on Microplasmas, to be held on April 3-6, 2011, Paris, France
1. W. Zhu, V. S. Johnson, R. Wang, J. Lo Re, J. Mahoney and J. L. Lopez, Atmospheric Pressure Plasma Jet Matrix (Talk)
2. J. M. Mahoney, W. Zhu, V. S. Johnson, and J. L. Lopez, Electrical and Optical Emission Measurements of a Capillary Dielectric Barrier Discharge in Atmospheric Pressure Air and Argon (Poster)
3. V. S. Johnson, W. Zhu, J. Lopez, Cathode Boundary Layer Discharges with Various Cathode Materials (Poster)
4. R. Wang., J. Lo Re, W. Zhu, K. H Becker and J. L. Lopez, Characterization of a DC-Driven, Atmospheric-pressure, Non-thermal He/O2 Plasma Microjet (Poster)

5. J. M. Mahoney, W. Zhu, D. Palacios, and J. L. Lopez, Vacuum Ultraviolet (VUV) Emission from a Fast-pulsed Dielectric Barrier Discharge in Argon (Poster)
6. V. S. Johnson, W. Zhu, S. Sivaram, R. Wang, J. Lo Re, J. M. Mahoney, J. L. Lopez, Low Temperature Atmospheric Pressure Helium Plasma Jet in Flexible Tubings (Poster)

Peer Reviewed Journal Publications:

- W. Zhu and J.L. Lopez. DC Nonthermal Atmospheric-pressure Plasma Microjet. Plasma Sources Science and Technology. In Press (2012).
- D.A. O'Brien, W. Zhu, and J.L. Lopez. Student Experiences with Plasma Phenomena. IEEE Transactions on Plasma Science. Vol. 39, Issue 11, p. 2584-2585 (2011).
- R. Wang W. Zhu, J.J. Lo Re, J. Zhang, J. Fang, and J.L. Lopez. Laminar-to-Turbulent Transition of a DC Helium/Oxygen (2%) Plasma Microjet. IEEE Transactions on Plasma Science. Vol. 39, Issue 11, p. 2374-2375 (2011).
- V.S. Johnson, W. Zhu, R. Wang, J.J. Lo Re, S. Sivaram, J. Mahoney, and J.L. Lopez. A Cold Atmospheric-Pressure Helium Plasma Generated in Flexible Tubing. IEEE Transactions on Plasma Science. Vol. 39, Issue 11, p. 2360-2361 (2011).
- J. Mahoney, W. Zhu, D. Palacios, V.S. Johnson, and J.L. Lopez. Footprints of a Fast- Pulsed Dielectric Barrier Discharge. IEEE Transactions on Plasma Science. Vol. 39, Issue 11, p. 2182-2183 (2011).
- J. Mahoney, W. Zhu, J. Lopez, V. Johnson, Electrical and Optical Emission Measurements of a Capillary Dielectric Barrier Discharge, the European Physical Journal D: Atomic, Molecular, Optical and Plasma Physics, 60, (2010) 441
- P. Sun, Y. Sun, H. Wu, W. Zhu, J. Lopez, W. Liu, J. Zhang, R. Li and J. Fang, Atmospheric pressure cold plasma as an antifungal therapy, Applied Physics Letters, 98 (2011) 021501
- K. H. Becker, H. Kersten, J. Hopwood, and J. L. Lopez. Microplasmas: scientific challenges & technological opportunities. European Physics Journal D. Vol 60, 437- 439 (2010)
- J. Lopez. *Ozone Generation with Cold Plasmas for Water Treatment Processes*. Chapter 2 in Biological and Environmental Applications of Gas Discharge Plasmas. Editor - Graciela Brelles-Mariño. Nova Science Publisher Inc. p. 33-48 (2010)
- G. Vezzú, J.L. Lopez, A. Freilich, and K. Becker. *Optimization of Large-Scale Ozone Generators*. IEEE Transactions on Plasma Science. Vol. 37, No. 6, p. 890-896 (2009).

IV. PATENTS

There were no patents filed as a result of this research project work.

V.   STUDENTS AND PERSONNEL SUPPORTED

Students:

There was a total of 1 graduate student, 18 undergraduate students, and 10 high school students from local area high schools directly supported by this project. There was also collaborations with various local area public high schools and the American Chemical Society's SEED program that supported student researchers and we hosted in our research laboratory.

Student Achievements:

Kamal Shah won a gold medal in the 52nd Hudson County Science Fair for his research conducted in the CMST in 2009 (http://www.nj.com/news/jjournal/index.ssf?/base/news-4/126932552476100.xml&coll=3). He was also placed 2nd in Northern Jersey Junior Science and Humanities Symposium (certificate attached).

Kamal Shah also won a gold medal in the 53rd Hudson County Science Fair for further research conducted in the CMST in 2010 (http://www.nj.com/hudson/index.ssf/2011/03/two_winners_of_the_53rd_annual.html). He was recommended to compete in the Intel International Science and Engineering Fair in Los Angeles.

Kamal Shah was admitted to Rice University with scholarship.

Yacine Fares won a silver medal in the 53rd Hudson County Science Fair for his research conducted in the CMST in 2010

Yacine Fares was admitted to Princeton, Yale, Harvard and Columbia and chose to attend Harvard University.

Mervy Michael was awarded a first place award at the American Chemical Society's presentation which took place at Seton Hall University in early September 2011.

Mervy Michael awarded the second place award at the Research Poster Session XIV – ACS that took place at St. Joseph's College in New York on Saturday February 4th 2012.

Mervy Michael at the 54th Annual Hudson County Science Fair which was held on March 12th, 2012, she received a series of awards. The first was the Water Resource Award presented by the NJWEA (NJ Water Environment Association), which is $500.00 and an award plaque which will be awarded to me at the NJWEA's 97th annual conference which will be held at Bally's Casino and Resort in Atlantic City on Wednesday May 16, 2012, as well as the Stockholm Junior Water Prize Regional Award. Also at the Science Fair I was awarded a gold medal in the Environmental Analysis

category, among 18 other gold medalists in 17 other categories. Two days later on May 14th, 2012 she went on to super- judging competing with the other gold medalists. She was one of the top two winners. Mervy will be traveling to Pittsburgh, Pennsylvania from May 12th – 18th as one of the representatives of Hudson County at the Intel International Science and Engineering Fair.

Various articles links about Mervy Michael's achievements:
http://www.nj.com/jjournal-news/index.ssf/2012/03/top_two_winners_of_hudson_coun.html

http://www.nj.com/jjournal-news/index.ssf/2012/03/grammar_school_medalists_speci.html

http://www.nj.com/jjournal-news/index.ssf/2012/03/19_gold_medalists_to_face_off.html

VI.   Interaction with Academia, Industry, and Federal Laboratories

There was direct collaborative research work done with the following national and international partners over the period of this research project. This is a list of the various established interactions:

Peking University, Beijing, China
Polytechnic Institute of New York University
Drexel University
UC Berkeley
University of Michigan, Ann Arbor
Old Dominion University
NYU Dental School
University of Medicine and Dentistry of New Jersey
Princeton Plasma Physics Laboratory
Case Western Reserve University
Texas A&M University
University of Notre Dame
University of Southern California
Stanford University

The United States Army Armament Research, Development and Engineering Center at Picatinny Arsenal
Algitron (joint STTR proposal)
Busek
The Linde Group